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Experimental mercury ARC rectifier.

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EXPERIMENTAL MERCURY ARC RECTIFIER

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RECTIFIER

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EXPERIMENTAL MERCURY ARC RECTIFIER

by

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of the requirements
for the degree of
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PREFACE

The mercury arc rectifier, for changing alternating current to direct current, was first utilized by Cooper-Hewitt in 1903 and since then has gone through many stages of development. As a matter of fact, only relatively recently have scientists begun to solve some of the mysteries of the mercury arc and discover more of the properties of the mercury itself. Foremost in the development of this field in the present day are Max Hoyaux, H von Bertele, R. Ledrus, R. Neirynck and M. Steenbeck of Europe and L. Tonks of the United States. This is by no means a complete list as many others have aided the development in some less direct manner.

This paper concerns experimental work on a controlled mercury arc rectifier tube of special design, having a mercury anode and cathode and fired by electrostatic means first tried by Cooper Hewitt. The investigation is not complete because of difficulties encountered in the operation of the rectifier. These difficulties are noted as well as comments on recent encouraging developments brought about by the afore mentioned scientists.

The writer is indebted to Professor William C. Smith of the U.S. Naval Postgraduate School for his assistance and cooperation in the experimental work carried out. The writer also wishes to express appreciation to Mr. R.S. Tice for making available the necessary tubes and equipment for the work, and to Professor Sydney H. Kalmbach of the U.S. Naval Postgraduate School for his work in repairing damaged tubes.

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CHAPTER I

INTRODUCTION

1. Rectification.

In the infancy of the electric power industry all generation and distribution was by direct current. For the service of a local and limited area this was acceptable and, in fact, desirable because of the flexibility of the D.C. motor. With the expansion of the industry and with the development of A.C. machinery, conversion to alternation current systems became almost universal. Since there are many fields in which direct current performs the work better than alternating current, and since most electricity is produced today with alternating current, there arose a need for changing alternating current to direct current. There are many ways of accomplishing this changeover, some mechanical others electrical. Actually the problems for rectification have been with us since the first rotating electrical generator was constructed to produce direct current. The rectifier in this case was a mechanical operation of switching, or commutation, when the windings in the rotor of the machine went through an area of zero flux. This paper will consider an electrical method--the proven mercury arc rectifier--with a somewhat different construction and control of rectification.

2. Scope.

This paper will be divided into two main parts. The first part will deal with an experimental tube developed by Mr. R.S. Tice and associates of the Tice Electrical Shop, Monterey, California. Due to some unfortunate circumstances these experiments were not carried to completion.

The second part will discuss some of the interesting phenomena and aspects observed during the operation of the experimental work as well as some recent advances in the mercury arc rectifier field. The work of the scientists mentioned in the preface as well as many articles from this country will be drawn on heavily for this part of the paper.

3. The Experiment.

The experimental results, obtained from the mercury arc tube used, are not as complete as would be desired but they do seem to show that this type of tube has its advantages as well as disadvantages. The advantages which seem to show up are that the tube does not require an igniting current and electrode as commonly employed, however, it does require external circuitry which accomplishes much the same purpose. Another advantage which is apparent is that the tube with its mercury pool anode and cathode does not have as great a source of contamination as with a carbon anode. This contamination by the carbon anode is the cause of the experiments not being carried any further. The mercury failed to rectify because of a film, much like slag, covering the surface.

CHAPTER II

THE TUBE

1. Construction

The mercury arc tube used in the experiments is shown in Fig. 1 and a cutaway drawing Fig. 2 . The main setup used in the experiments is shown in Figs. 3 & 4 .

The tube was constructed of pyrex glass with tungsten cups to which the leads for the anode and cathode were connected by large alligator clips. As shown in Fig. 3 , these metalic cups were the connection between the outside wire and the mercury. One of the difficulties in construction of the tube was this joint between the glass and metal. During operation of the tube either of the mercury pools could be the anode or cathode but because of the method used for excitation of the mercury the upper pool was required to be the cathode.

Ignition was accomplished by the use of a voltage on the carbon ring around the outside of the glass inside of which was the cathode mercury pool. It will be noticed that there is a semicircular channel inside the tube, Fig. 2 , in which the cathode mercury pool is contained. The carbon ring was simply Carbon-X, a standard stock item carried in electronic supply stores, which was painted on the outside of the glass. A lead was taped and painted to the ring for bringing in the ignition signal.

Near the top of the dome is a carbon anode which was placed in the tube for comparison purposes, i.e. operation using a carbon anode as against a mercury anode.

The amount of mercury in the tube was not critical and a tremendous excess was used, the total being about four pounds. Some channels were formed in the glass below the cathode pool in order that the length of the path of overflow mercury would be increased over that of a direct line from cathode to anode. This was done to prevent a short circuit from being caused as the overflow mercury went from cathode to anode. This was found to be unnecessary because the amount of mercury flowing at any one time was much less than that which would be required for a short circuit. The overflow was caused by the condensation of mercury vapor on the dome of the tube running down the sides and filling the cathode pool. This is actually the purpose of the dome on glass-built mercury tubes, that is, for condensation and heat dissipation.

2. Operation

The operation of this rectifier tube is the same in principle as any mercury arc rectifier, except that it has a novel manner in which excitation is applied to the tube. The other unusual feature is the mercury anode and cathode.

The excitation for the tube is a high voltage pulse which is applied to the carbon ring which is painted outside the cathode pool. The voltage path is through the glass to the cathode and back to the exciter either through the normal circuit or through an extra lead from the cathode to the exciter circuit. A schematic of the exciter circuit is shown in Fig. 5 . As will be noted the exciter circuit can be easily designed for full wave rectification and a phase shifter circuit can be included as shown.

The capacitor C_1 is charged through resistor R_1 with plate voltage. When the tube V_1, a 2050 thyratron, is fired the condenser C_1 discharges through this low resistance to ground. The circuit is completed through the low voltage side of an auto-transformer. This induces a very high voltage pulse on the high voltage side of the transformer and this is coupled to the carbon ring on the tube.

The voltage on the grid of the tyratron is in phase with the voltage to be rectified, however, this phase may be changed by use of an auxiliary device through 180 electrical degrees. The result is that the grid will exceed its critical voltage during some part of the positive voltage excursion and thereby allow the tube to conduct. Varying the phase of the grid changes the percentage of the positive swing that the tube V_1 will conduct. As explained above, V_1 conducting produces a high voltage on the control ring of the mercury arc tube causing it to conduct. Once started, conduction through the mercury arc tube continues during the remainder of the positive half cycle of anode voltage. Thus the length of the D.C. pulses through the mercury arc tube determine the average or D.C. power transmitted.

CHAPTER III

EXPERIMENTAL RESULTS

1. Excitation.

In order to better study the effects of different voltages and currents through the experimental tube, it was thought that D.C. potentials impressed, anode to cathode, would give the best results. Also, since the exciting circuit made no provision for different frequencies and voltages a separate source for both of these quantities was used.

The D.C. anode to cathode voltage was furnished by an adjustable voltage generator of 500 volts maximum. The exciter voltage posed somewhat of a problem as it was not known what voltage was required or the length of the pulse that could be tolerated. Since these were not known to any degree at all, the first thought was to use a 60 cycle source with a step-up transformer. This was tried using a 3,000 volt output voltage stepped up from 110 volts. On application of this voltage to the carbon ring—which will be called the grid—no conduction was obtained with up to 500 volts from anode to cathode.

It had been previously noted during operation of the tube that, with the exciting voltage to the grid which gave proper operation, the mercury in the cathode pool bubbled in a manner similar to boiling. With the above 60 cycle, 300 volts impressed the mercury had no movement at all.

A 400 cycle step-up system was then considered but was ruled out because of the high voltage requirements and equipment difficulties. The next effort was to use a signal generator, running the signal through an amplifier and then through a 6L6 with a relay as the plate load as shown in Fig. 6. The other circuit of the relay closed contacts which charged

a capacitor from a D.C. source and then switched the contacts to discharge the condenser through the auto transformer. The auto transformer was an ordinary heavy duty automobile spark coil. Depending on the value of D.C. voltage used, enough voltage was obtained to excite the cathode into the conduction region.

The auto transformer had to be pulsed no slower than about 10 cps. Any rate lower than this failed to ignite the tube. The upper limit at this time was determined by the speed at which the relay could operate and this, of course, varied with each relay used. The lower pulse rate might also have been a function of the relay, in that the speed of closure would affect the output pulse.

The table below will give some idea of the variation of exciter and anode voltages, with the lowest current flow to give reasonable assurance that the tube would continue to conduct for a period of several minutes. This is also shown graphically on Fig. 7. The frequency of the relay was 10.5 cps. This data seems to show a random correlation indicating there is no well defined critical value of exciter potential.

Exciter, Anode, Cathode Voltage Relationships:

Exciter voltage (grid)	Ee (pulse)
Anode Voltage	Ea (D.C.)
Load Current	I (D.C.)
Tube Drop	Et (D.C.)

Ee	Ea	I amps	Et volts
121.5	285	2.3	16
121	250	2.0	16
116	260	2.1	16
118	274	2.2	16
120	285	2.3	16

The tube drop is noticed to be constant at 16 volts and is the D.C. value measured voltage difference between anode and cathode. This value seemed to remain constant no matter what current or voltage was measured as long as the tube was kept somewhat near a constant temperature.

2. Tube Drop Runs.

A run was made with the tube kept at nearly a constant temperature with an eight-inch fan circulating room air by the tube. This particular run showed that the tube drop would increase somewhat with increased current as would be expected. However, the drop was fairly constant over a considerable current range, Fig. 8. The tube drop itself was not a constant quantity but varied over a range of about a volt or so.

The temperature of the tube was measured by a centigrade thermometer taped to the dome of the tube. This is a very crude method of temperature observation but it is believed to give relative results which is all that was desired. In order to get more accurate data, other experimenters have used a block of copper machined to the curvature of the glass and the thermometer carefully fitted into a hole in the copper. This latter method gave data which was useable for calculations.

This experiment was not carried to higher current ratings, however, the tube has been operated at nearly 50 amperes when cooled in an oil bath.

For comparison purposes a run was made without any cooling except by the still air around the tube. This is shown in Fig. 9. It is to be noticed that both temperature and tube drop increased at a very rapid rate with increase in current. At one time the tube was left on for

about an hour with an initial current of about 10 amps. A measure of the tube drop showed it to be over 150 volts and the tube had an eerie glow. No temperature measurement was made, however, it was hot enough to make the supporting wood structure smoke.

Since a carbon anode had been installed in the tube a run was made to compare the operation under the two conditions, i.e. a carbon anode versus a mercury anode.

An interesting path of current flow was observed during this run. The path was a tube about ¼" in diameter following more or less the curvature of the glass from cathode to anode. Where this tube contacted the carbon anode, the anode glowed red and after shutdown showed definite signs of burning where this heating occurred.

3. Deionization Time.

Since it would be of interest to know the frequency at which rectification would take place, the deionization time was determined. The importance of deionization time is that the tube must be deionized before reverse voltage is applied, otherwise a backfire would likely occur and also the grid would not have control of the next positive pulse. A backfire in this case is that the tube conducts in the direction opposite that desired, this of course means that the tube is nearly a short circuit instead of a rectifier. There are other types of backfires in multianode tubes, so called when the arc jumps from anode to anode.

It was found that if the current--with D.C. anode to cathode voltage applied--was near 3 amps, the tube would continue to conduct for a period of up to a minute or so before it was extinguished. Because of

this the current was kept near 1.5 amps during the run to determine deionization time.

The setup included an oscilloscope, Navy Model TS-239A/UP, placed across anode to cathode. From this it was determined that the time for the voltage to drop to zero, after being fired by a pulse on the grid, was 81 microseconds from the peak voltage to a value which essentially was zero. A picture of the wave shape was taken using a Techtronix Oscilloscope, Model 512 and a polaroid camera. The results are shown in Fig. 10.

From these figures it can be seen that the frequency of operation must be considerably less than

$$f = \frac{1}{T} = \frac{1}{2(81 \times 10^{-6})} = 6{,}100 \text{ cps}$$

Because the spark coil failed to give proper voltage above about 800 cps it was not possible to determine experimentally the maximum frequency of operation. The anode cathode voltage was about 16 volts which was the normal tube drop. The important point was to keep the current below the value of 3 amps so that the tube would deionize after each impulse of voltage to the grid. In this manner a recurrent trace was obtained on the oscilloscope.

4. Missfires.

It was noticed during the operation of the tube that even when D.C. voltage was placed between anode and cathode, unless a current of about 6 amperes was run through the tube, the tube would extinguish itself after a time. No explanation for this occurrence is offered although it may be surmised as being due to a rise in temperature--and therefore a

rise in pressure within the tube--or due to some impurity on the surface of the mercury. From this observation it was decided to determine if the tube would rectify each cycle of alternating input voltage. It was found that it failed to rectify more often when the carbon anode was used than when the mercury anode was used. Figs. 11 and 12 show results of very limited duration runs using the mercury anode. This was obtained by use of an Esterline Recorder. Since the inertia of this recorder is rather large and the length of run short, the results were not considered of much significance.

In order to better evaluate the tube a miss-fire counter circuit was constructed as shown in Fig. 13. A Hewlitt Packard electronic counter was to be used to count the misses. The circuit functioned very well using a 60 cycle test input, however, on setting up the counter in conjunction with the tube, the tube would not ignite.

The grid voltage was increased, the anode to cathode voltage was increased but with negative results. The two other tubes which were available were also tested and they would not fire either. One tube was tipped so that the anode mercury touched the cathode mercury--with D.C. anode to cathode. This started the conduction but with results similar to those when using the carbon anode. There appeared to be a waterfall of the ionized path from cathode to anode without lighting the tube in its normal glow. As soon as this was noticed the tube was shut down with the result that most of the dome had become silvered by the mercury with a permanent deposit. The mercury in the pools was covered with a slag.

It was finally thought that operation with the carbon anode had severely contaminated the mercury of the tube used in that condition, as the mercury was covered with a heavy, dark, sooty slag. The tube that

had become silvered was thought to have either contaminated mercury or that the glass had not been clean enough. The third was found to have lost its vacuum.

An attempt was made to replace the mercury in the first tube with clean mercury, but while evacuating the tube just before sealing the tube developed a ruinous crack. No further attempts along this line were made.

The assumptions as to the reason for the failure of the tubes were given more support when it was learned that Westinghouse Electric Corp. had worked on a similar idea and had similar results. They had found that if the glass of the tube was too clean the tube would not operate, likewise if it had too much foreign matter on it, again the tube would not operate.

5. Experimental Conclusions.

As far as the experiment was carried, the mercury anode-cathode combination appeared to offer advantages in several ways. The heat dissipation in this particular tube would seem to be better and there was not the contaminating effect of the carbon. It is realized, however, that carbon could possibly be purified and degassed so as not to contaminate the mercury as happened in this case.

It is felt that the external exciting grid circuit would require less power than the starting anode of the standard mercury arc rectifier. An easy method of phase shifting the grid voltage is available to obtain, in effect, a high current capacity as is available in the ignitron.

CHAPTER IV

INTERESTING SIDELIGHTS

1. Cathode Spot Anchors

Some rather interesting properties of the mercury arc rectifier were noticed during the experiment. One of the most obvious of these is the fact that the cathode spot fairly races over the cathode surface in a completely unpredictable manner. In the last decade much work has been done in an attempt to stop this random movement of the cathode spot and thereby increase the efficiency of the rectifier. By stopping the random movement of the spot, the possibility of more efficient heat transfer from the cathode may be obtained and thereby less mercury evaporation will result. Both of these are useful in making a smaller more efficient rectifier.

The first of these—the stopping of the random motion of the spot—has been the subject of a great deal of effort mainly by the Europeans. This consisted of attempts to get an anchor to which the spot will attach itself and thereby stopping its motion. This is not a new idea at all but has only been successful in the past decade or so. Many an attempt has been made using various metals and various configurations of metal anchors to which the spot would attach itself.

It has been found that molybdenum made the best anchor for several reasons, the main one of course being that the cathode spot would attach itself to this metal and the emission would change from a spot to a thin line along nearly the entire contacting edge of the two metals. The

next main feature of molybdenum which had ruled out many of the other metals to which the spot would attach, is that it was not attacked by the emission from the emission line causing the mercury to become contaminated.

Another factor which ruled out other metals—tungsten for example—was the fact that only relatively low currents could be carried with the spot anchored. Currents greater than this caused the spot to detach itself from the anchor and again take up its random motion. Fig. 14 is an example of the geometry of one of the early experiments used to determine these effects.

If the anchor be so designed that it presents a low heat resistance, the heat generated by the emission line is rapidly carried away from the mercury pool. The result of this is less so-called mass transfer or evaporation of the mercury. Mass transfer actually means that the number of molecules entering or leaving the mercury pool are not the same. The net difference collects on the walls of the tube. It was found by J. von Issendorf that splashing accounted for about 90% of the mass transfer from the cathode pool. This is attributed to an observed phenomenon which has been given the name "vapor jets." It has been proposed that these vapor jets are a series of cumulative rapid impacts and have been observed to cause erosion of the bottom of the cathode pool to a depth of about 12mm. Without mass transfer there are no vapor jets and with increased mass transfer the vapor jets increase. The obvious desire then is to decrease mass transfer and this can be done by increasing the heat flow away from the cathode pool by use of a low heat resistance anchor.

The desirability of an anchor has been brought out in its ideal form but the practical difficulties in manufacture and uses have not been dealt

with. This side of the problem is taken up in detail in the references. The anchor in effect is an island in the mercury pool to which a spot attaches itself. This results in less tube heating, less tube drop, and less loss due to mass transfer.

For better heat transfer through the anchor, attempts have been made to cool them by circulation of water inside the anchor. From this was devised the method for use with smaller rectifiers. In this, the cup containing the mercury was made of molybdenum and acted as the anchor. To the outside of this was added a copper ring for heat transfer and to this was added aluminum fins for cooling. A very compact, efficient, low capacity mercury arc rectifier was the result.

It is thought that developments in the field of anchors will ultimately result in a rectifier consisting of only a film of mercury with a droplet as a reservoir. This will require very careful control of the temperature gradient as can be seen from the evaporation which ensues when the temperature of the tube envelope and mercury pool differ greatly as in the case of the experimental tube considered in the first part of the paper.

2. Grid Excitation

The excitation of the tube under investigation is one of its unusual features and should be considered as to the method of obtaining it. Since it was found that some 25,000 volts was required in the form of a pulse it might be surmised that the excitation is due to an unusual effect caused by this high voltage. Much work has been done in this field, the original being done by J.S. Townsend, from whom a type of discharge is named.

If the voltage between two electrodes be increased above the well known Townsend or "dark" discharge, one of several forms of self sustaining discharge can occur. One type is the arc which is associated with a spark between the two electrodes. Another type of selfsustaining discharge is the corona discharge. This latter is believed to be the type which occurs between the carbon ring--grid--and the cathode pool of mercury. One of the requirements for this type is that it will occur in areas of small radius of curvature. From the appearance of the tube construction it would seem that this condition is not met, but by the same token corona discharges occur in a coaxial cable and also in transmission lines where some imperfection might be. From the observation of the action of the experimental tube, this might well be the case, in that there were surely differences in the thickness of the glass between the two electrodes--the mercury pool and carbon ring--as well as differences in the application of the carbon to the tube. This was further born out by the fact that the cathode was agitated only in small areas and not overall, even though the carbon ring encircled it. When the tube failed to fire, as has been explained, a Tesla Coil was used to excite the cathode through the carbon grid. This did not work and it is now reasoned that, had the carbon ring been removed, the concentration of the high voltage at only one sharp point, might have been enough to excite the cathode even though badly contaminated. This would not be satisfactory standard operation, however, because it was found in previous experiments by Mr. Tice, that if the voltage were concentrated in only one spot the glass would eventually deteriorate. The initial voltage starts an electron avalanche which ionizes the mercury in the

cathode. As soon as the ionization is started the anode takes over and continues the ionization of the cathode by bombardment with ions in the tube gas. This is the band-igniter principle discovered by Cooper Hewitt and used for starting the Cooper Hewitt lamps.

A serious difficulty with the band-igniter is that after a few hours of service the mercury tends to wet the glass which requires a higher exciter voltage to result in ignition. This was shown very vividly by one of the experimental tubes which became coated with mercury only after a few seconds of operation. The short time of operation would indicate that other factors entered into the failure. Such wetting was not observed to occur in the other tubes. The wetting is caused by amalgam, oxides, and such, which form during the operation of the tubes.

A modification of the Cooper Hewitt type igniter was devised by K.J. Germishausen. In this design, rather than the band around the outside of the tube, a wire, which is covered with a very thin layer of glass, is inserted into the mercury pool cathode. The glass layer is of the order of 0.003 to 0.010 inch thick. The wire is on the order of 0.040 inch diameter and made of tungsten. The ignition voltage required depends on two main mechanical factors, the thickness of the glass layer and the angle at which the wire is inserted into the pool. At about 45° angle for the wire, the ignition voltage is reduced to half that for a vertical wire. The voltage required for the 45° angle construction is about 1500 volts with quite a variation on either side of this value.

The advantage of this type of igniter is that it is in the warmest part of the pool—the middle. The amalgams and oxides formed tend to travel toward the cooler part of the tube, thus keeping the glass on the

igniter from becoming wetted. Thus one of the biggest drawbacks of the Cooper Hewitt band-igniter is overcome.

CHAPTER V

CONCLUSION

Though the experimental results obtained were on the whole so incomplete that no definite conclusions could be drawn, indications seemed to show that the tube does have merit in its method of phase control over the grid and therefore control over the D.C. output of the tube. It would seem that the maximum voltage would be less than that of a tube using a carbon anode but this was not investigated. Another advantage is that the contaminating effects of the carbon anode are reduced.

From this it is evident that the tube warrants further investigation before a realistic understanding of the tube's value will be known. It is thought that the refinement used by Germishausen should be incorporated in any new design. This would require the reversal of the cathode and anode so that the igniter could be placed in the middle of the pool.

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Fig. 1 THE TUBE

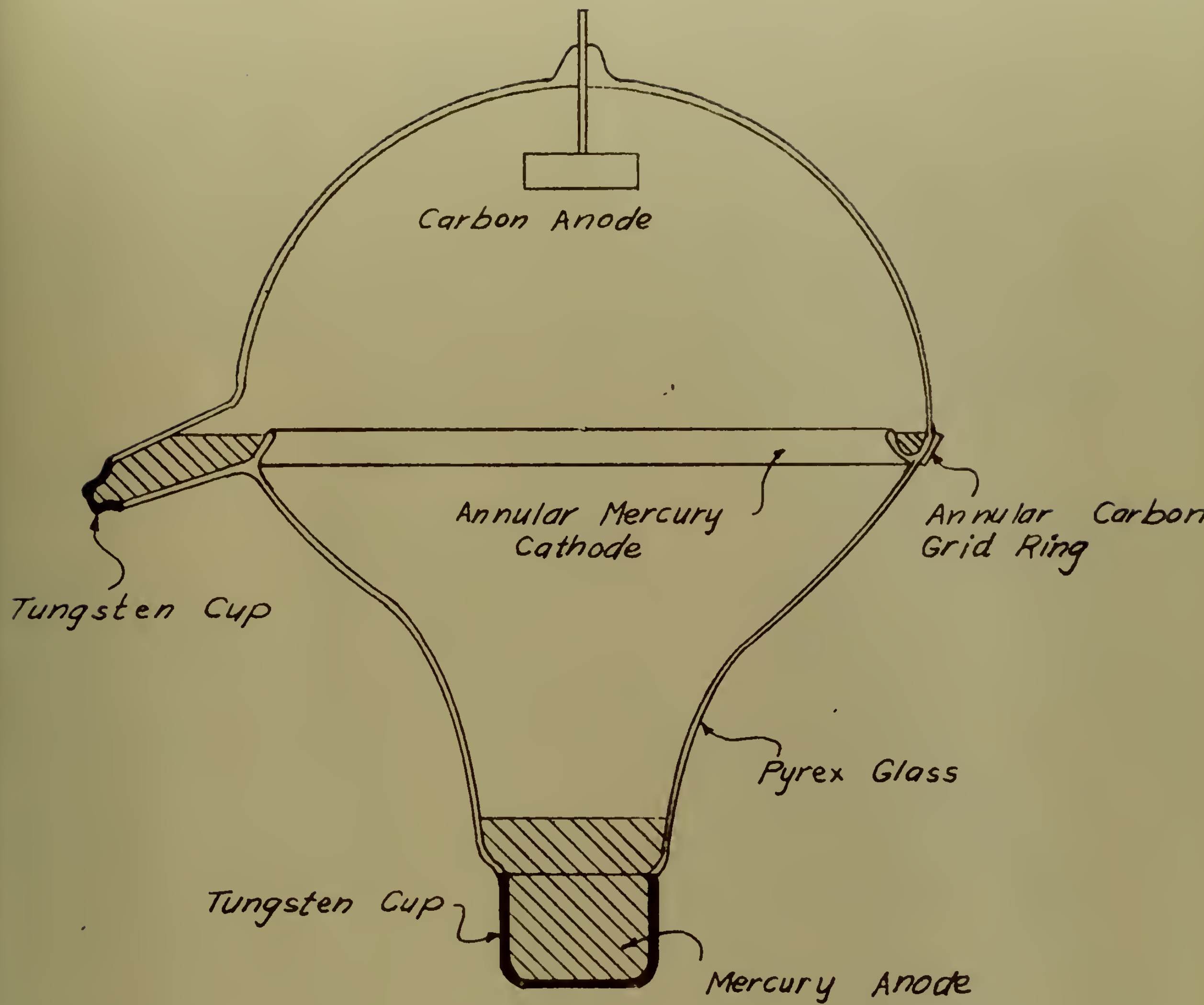


Fig. 2
Experimental Mercury Arc
Rectifier

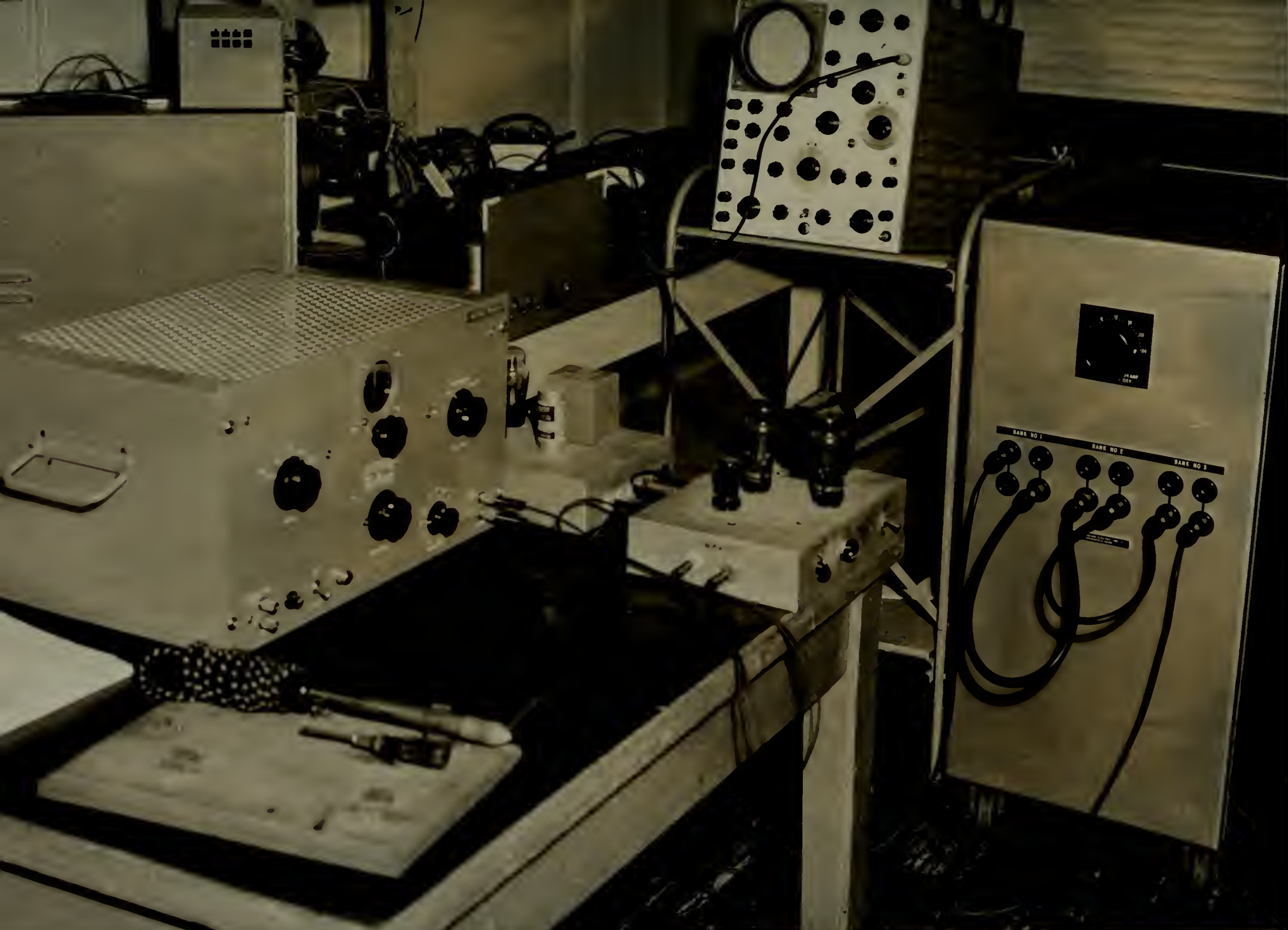


Fig. 3 INITIAL SET UP

Fig. 4 INITIAL SET UP

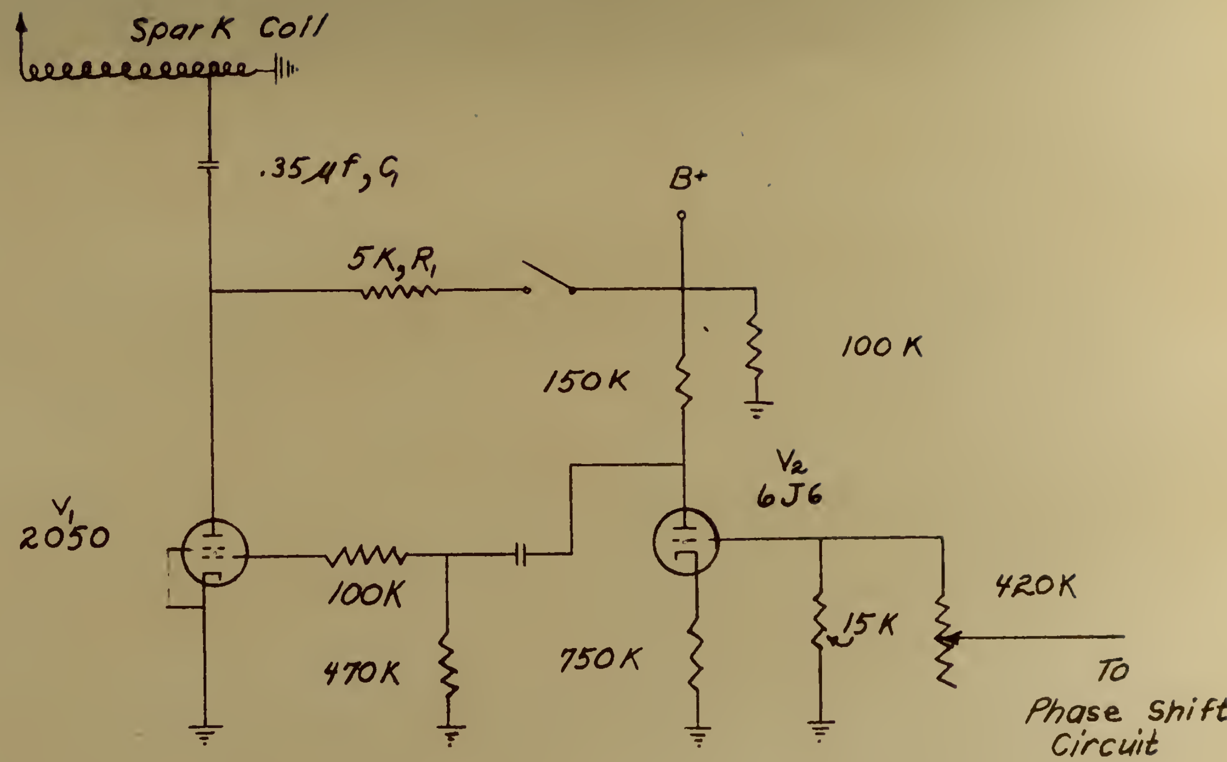


Fig. 5
Grid Exciter Circuit Diagram

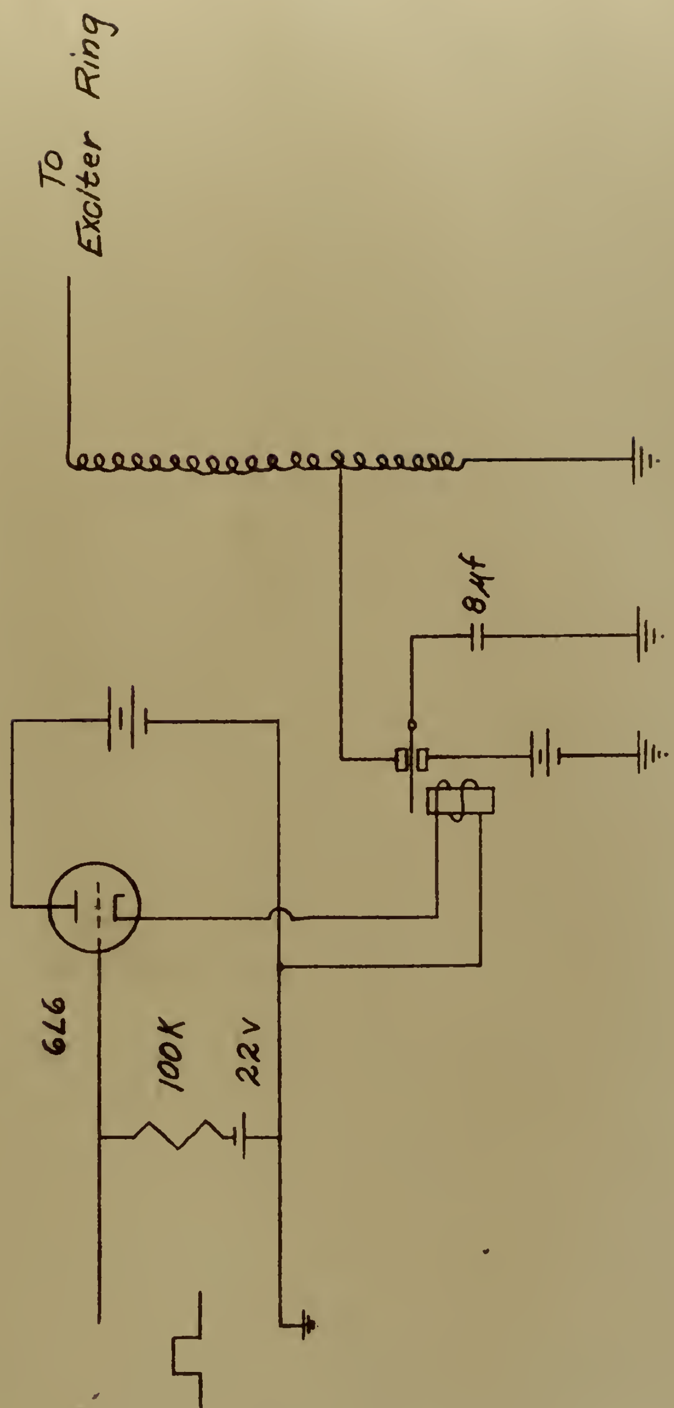


Fig. 6
Relay Circuit

Fig. 7
Mercury Anode & Cathode
No Cooling
D.C. Voltage Applied

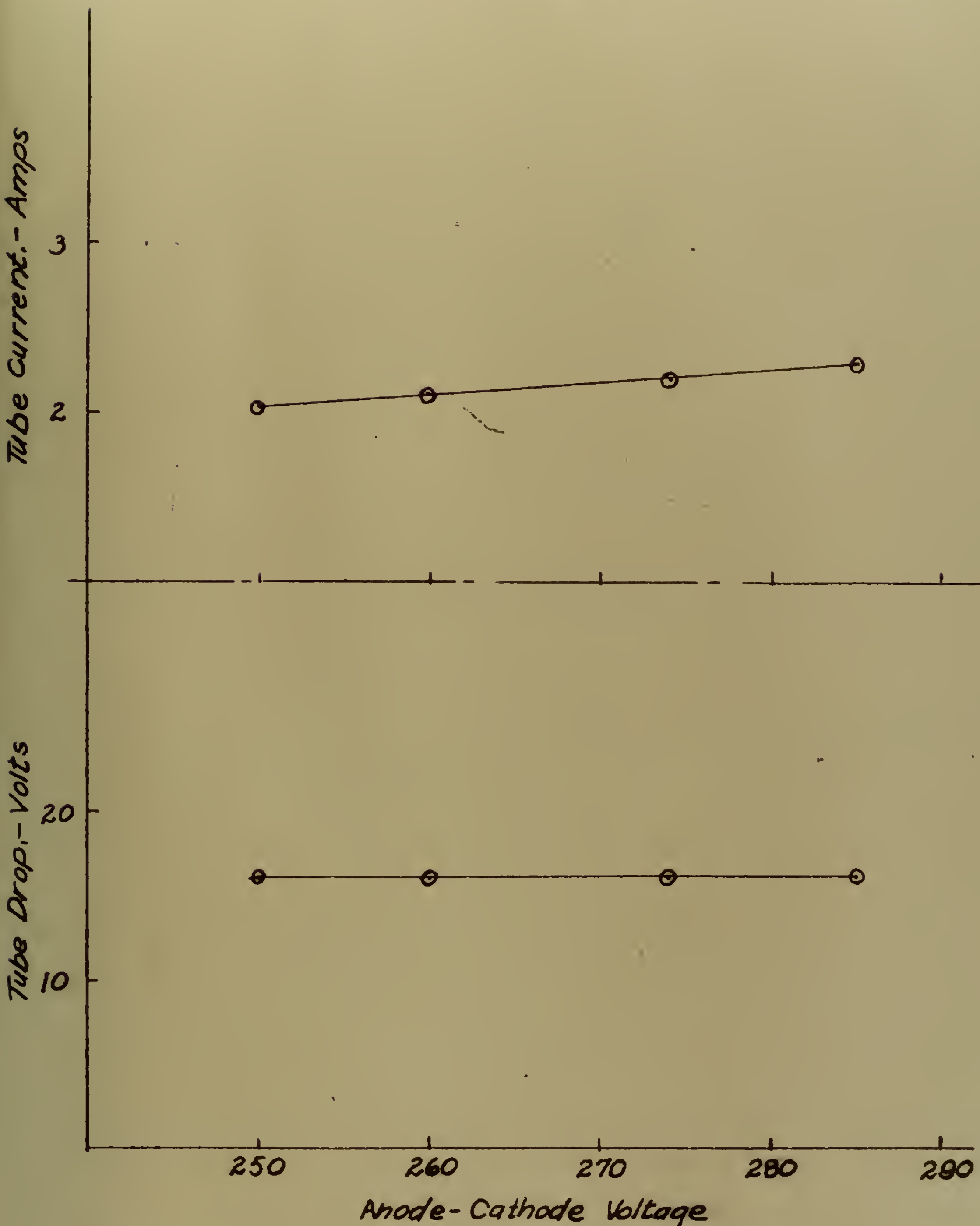


Fig. 8
Mercury Anode & Cathode
Cooled By 10 Inch Fan
D.C. Voltage Applied

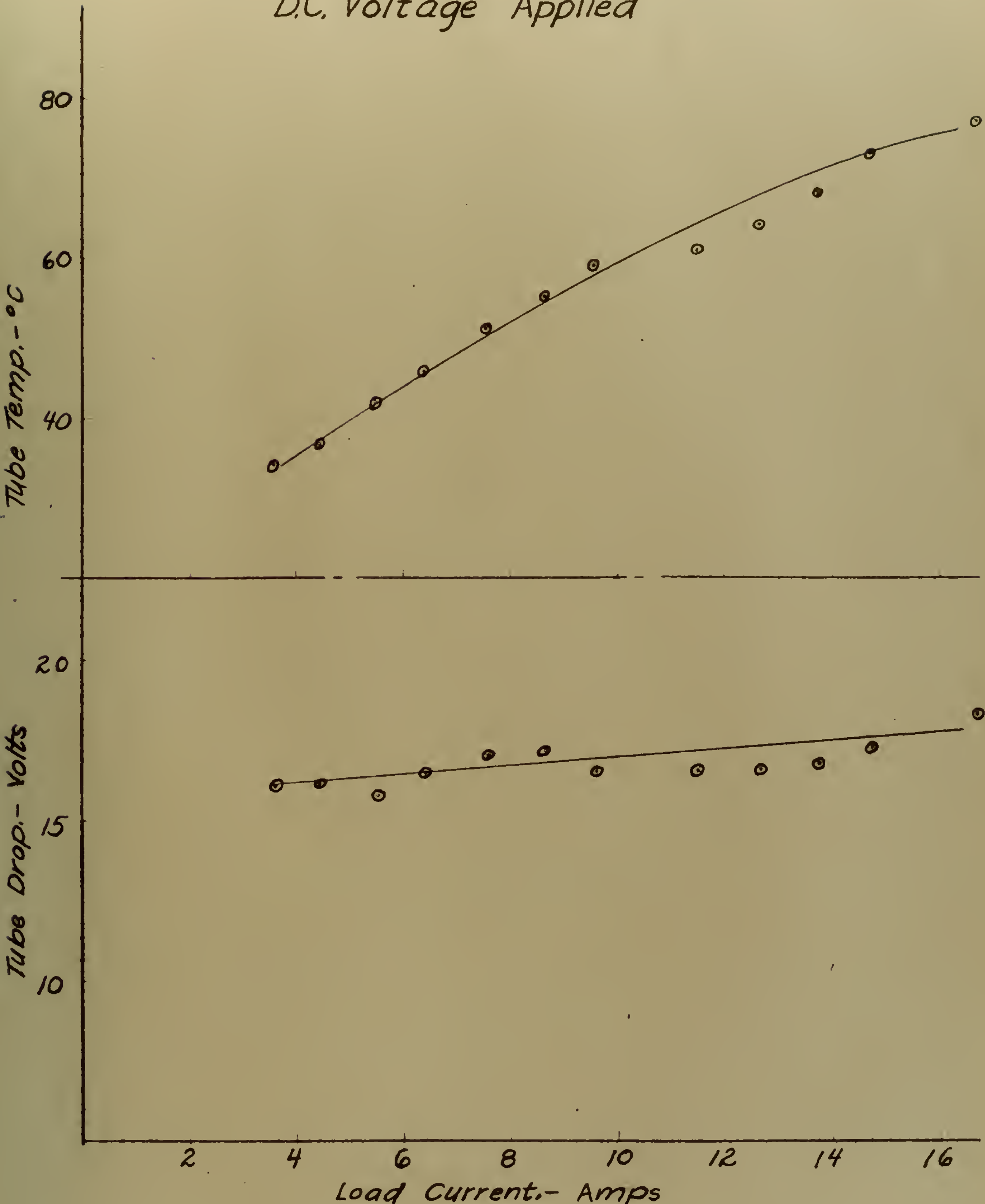


Fig. 9

Mercury Anode & Cathode
No Cooling
D.C. Voltage Applied

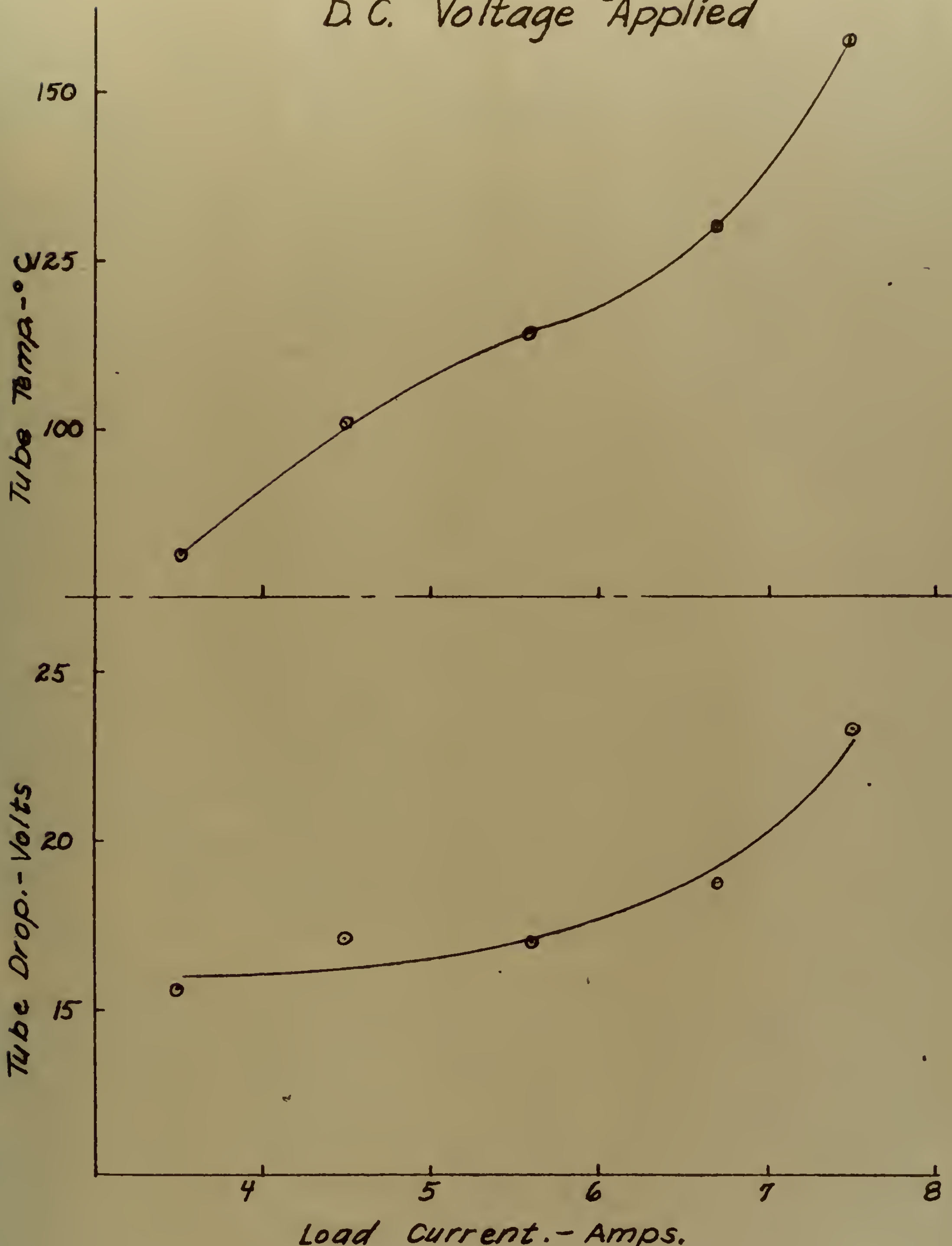
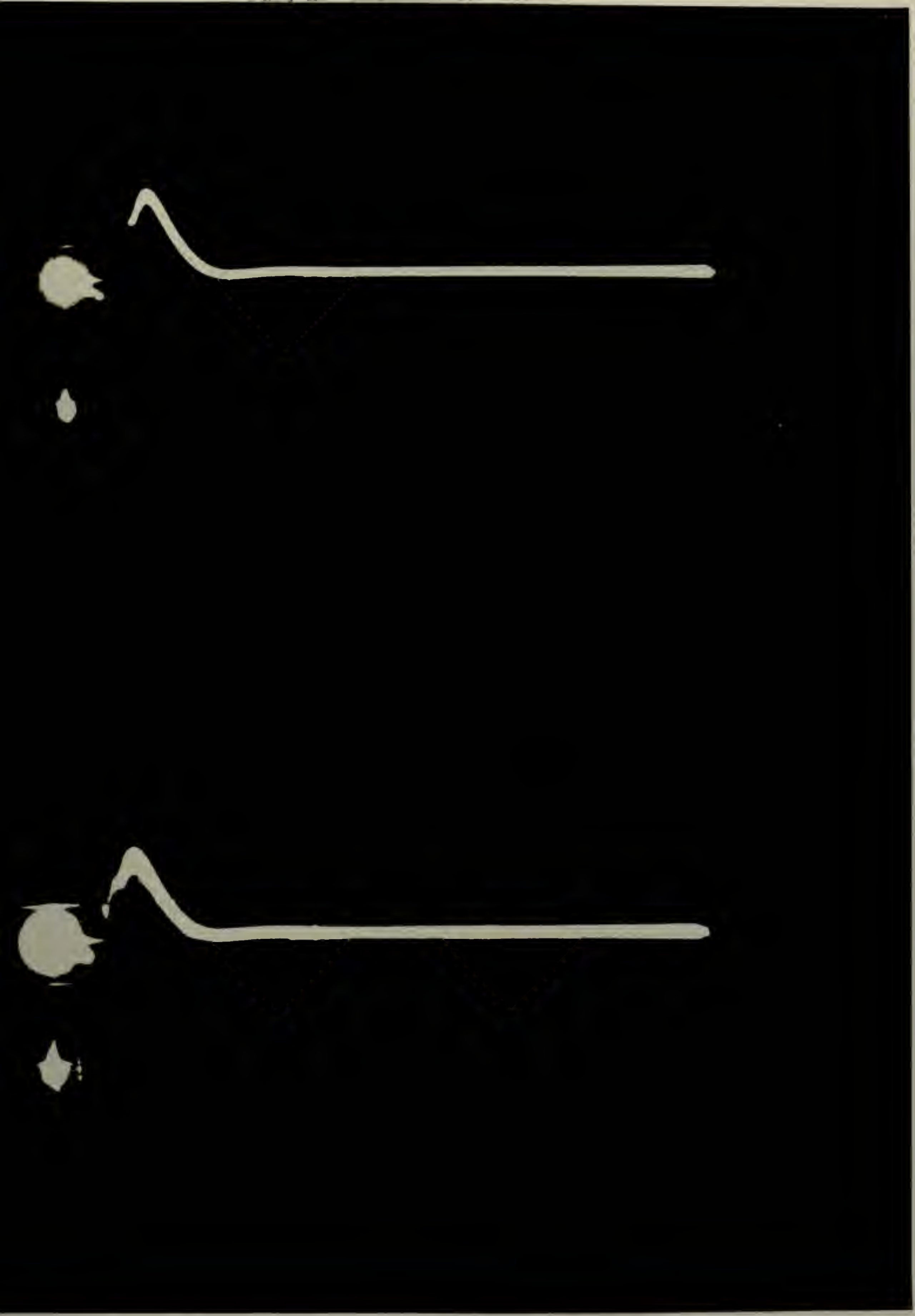


Fig. 10 DEIONIZATION CURVE



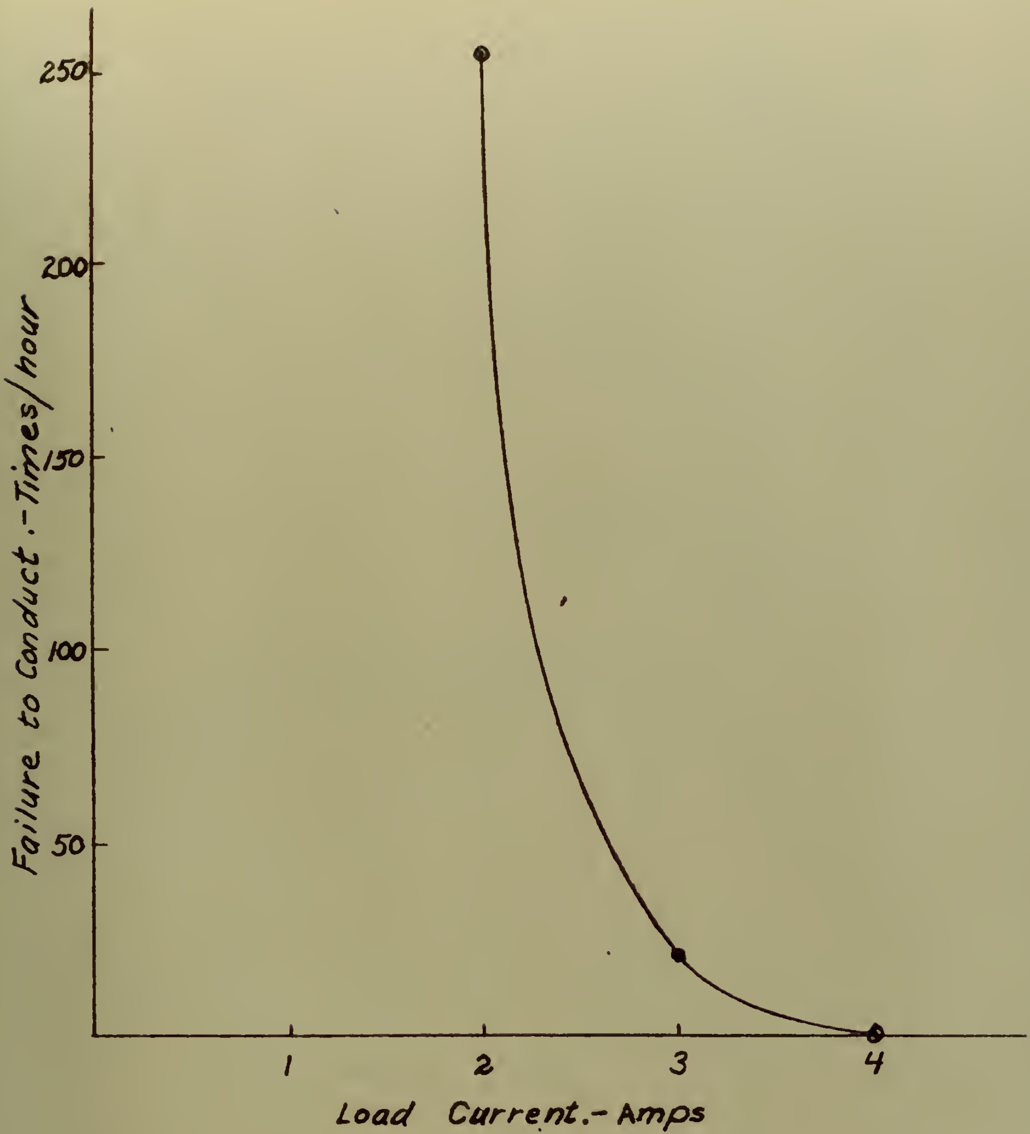


Fig. 11
Mercury Anode & Cathode
No Cooling, DC. Voltage

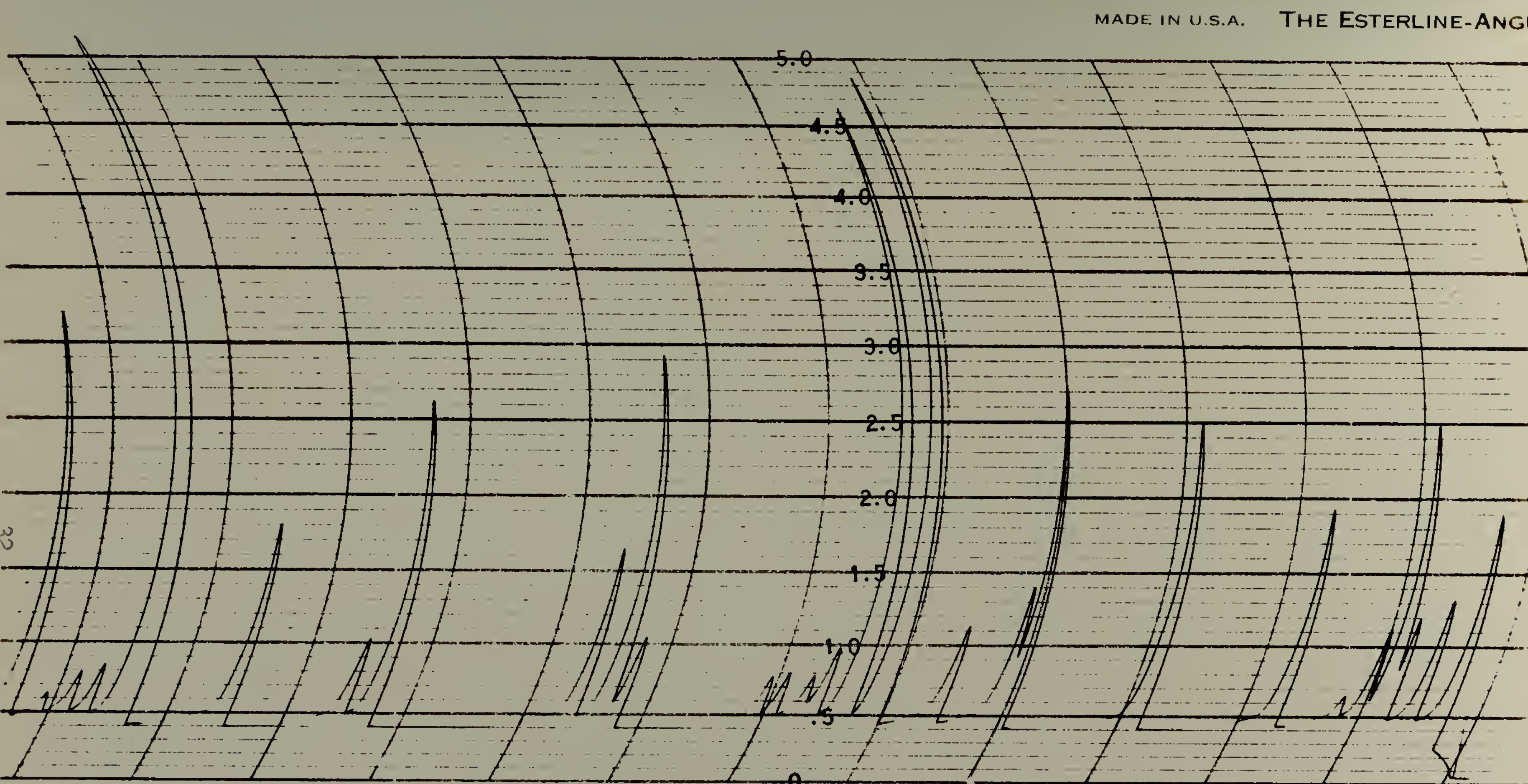


Fig. 12 TAPE OF MISS FIRES

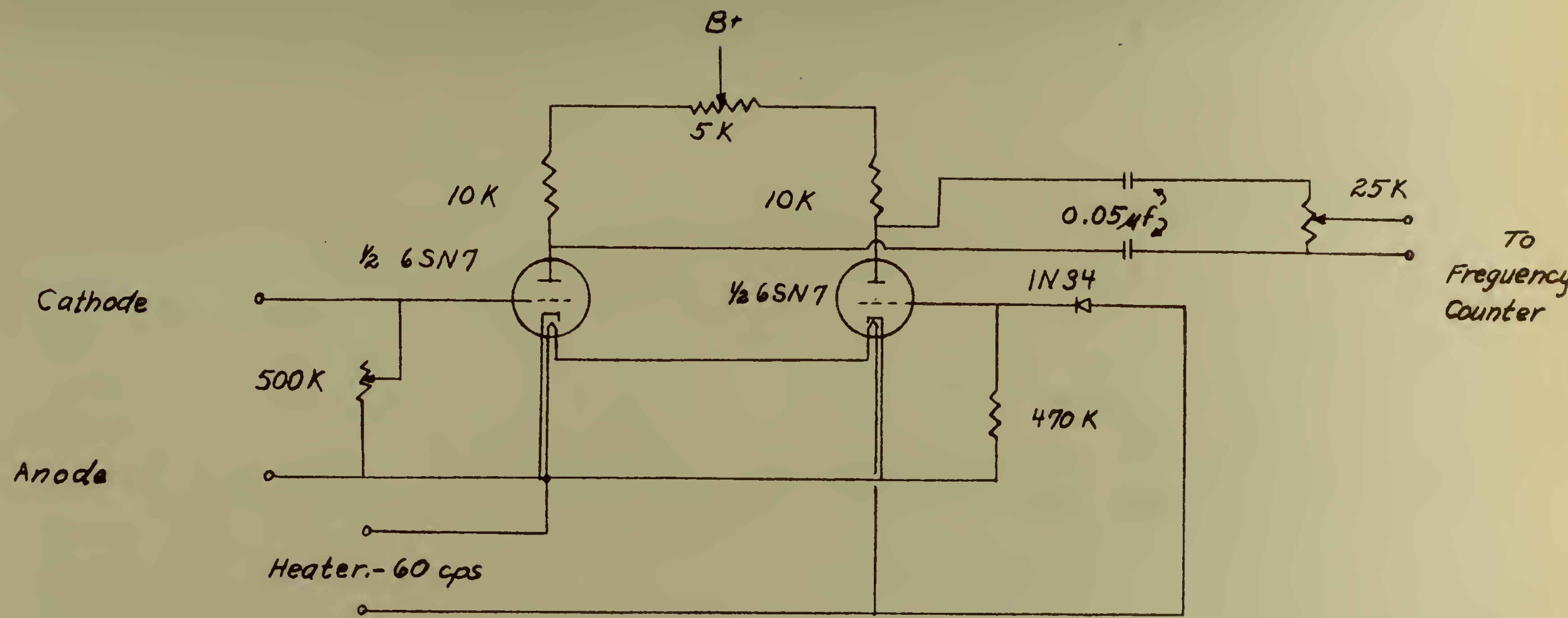


Fig. 13
Miss-Fire Counter Circuit

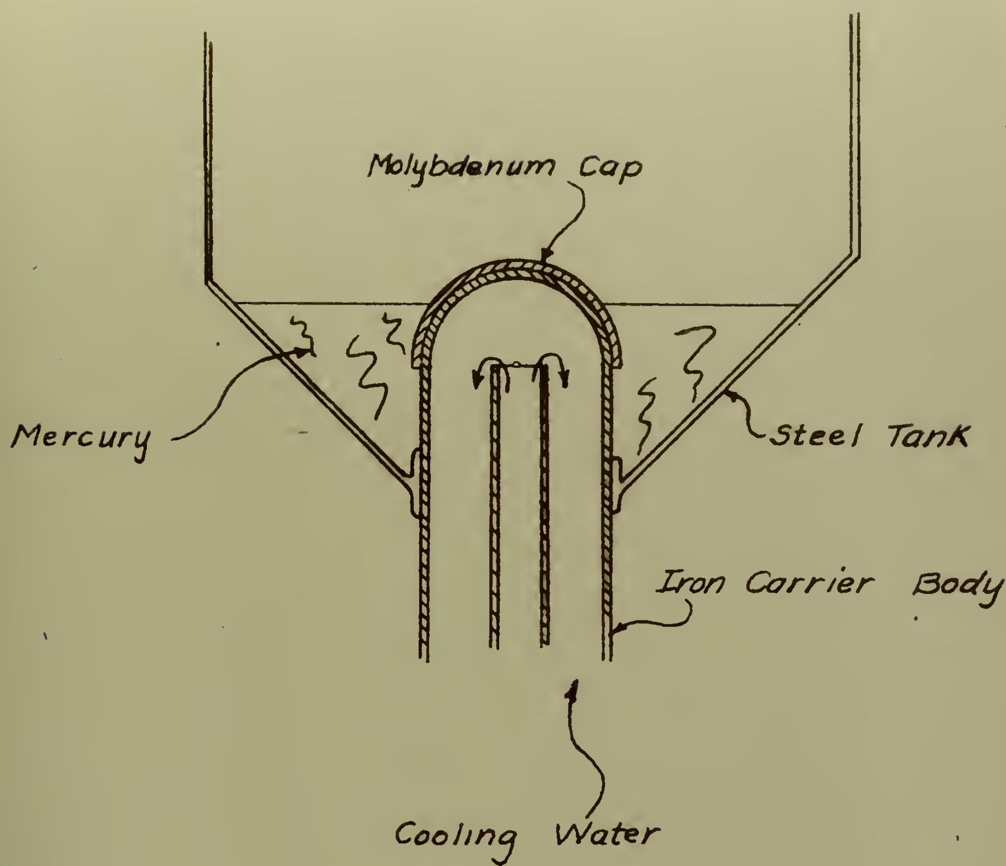


Fig. 14
Construction of Typical Anchor

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Thesis
T45 Thomson
Experimental mercury arc
rectifier.